HIGH SPEED QUADRANT CCDS FOR ADAPTIVE OPTICS

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ABSTRACT

The Johns Hopkins University is developing an adaptive optics coronagraph for the study of circumstellar material at high resolution. The first generation instrument corrects for image motion, ie. wavefront tilt, using an image motion sensor coupled to a high speed tip/tilt mirror. The image motion sensor is built around a quadrant CCD which detects offsets from the null position. We discuss the performance of this device and present results demonstrating its operation in the laboratory.

INTRODUCTION

The angular resolving power of ground-based optical telescopes is limited, even at the best sites, by atmospheric turbulence to 0.5-1.0", and so the diffraction limit of astronomical telescopes is seldom achieved except at long wavelengths. Diffraction limited images may only be obtained by application of image reconstruction techniques following an observation or by a real time approach such as adaptive optics.

The effect of atmospheric turbulence on an image may be considered in terms of two components, wavefront tilt and wavefront distortion, resulting from phase and amplitude perturbations to the incoming wave. With adaptive optics it is possible to correct in real time for the phase distortion of the perturbed wavefront. An adaptive optics system usually consists of two elements, a tip/tilt mirror to correct for large first order wavefront tilts, and a multielement adaptive mirror to correct for higher orders of distortion. For a telescope aperture (D) of size $\sim r_o$, the main source of image degradation is image motion (~60%) and so for telescopes where D ~few r_o, image motion compensation alone can provide a major improvement in image quality. A real time correction is particularly advantageous since it allows the concentration of light into a smaller spot size yielding an increase in signal to noise and spatial resolution in the detected image. Adaptive optics, therefore, has the potential to give a major improvement in the performance of ground based telescopes and should be seen as complementary to other techniques of high resolution imaging.

The Johns Hopkins University has recently started a program to develop adaptive optics for coronography, with the purpose of studying, at high resolution, the distribution of circumstellar material around bright stars such as β Pictoris (Smith and Terrile 1984) in the optical and near-IR. The program is evolutionary in its approach, with the correction for wavefront tilt (image motion) being implemented initially, to be followed by a fully adaptive system based on a membrane mirror to correct for wavefront distortion at a later stage. The instrument will initially operate on the Swope 1 metre telescope and later on the 2.5 metre telescope at Las Campanas.

There are several advantages to using adaptive optics in a coronagraphic system. The light from the central star under observation is usually blocked by an occulting mask and so may be redirected for wavefront sensing, removing the requirement for a guide star close to the target. Thus, the small isoplanatic patch size at optical wavelengths does not constitute a problem, and, since the circumstellar material of interest is typically within a field of $1'$, a good adaptive correction should be possible for most objects under study. In addition most of the program targets are bright, so there is a relatively high photon flux level for the wavefront sensor detector.

THE ADAPTIVE OPTICS CORONAGRAPH

In figure 1 we show a schematic of the Johns Hopkins adaptive optics coronagraph, as it is currently implemented, for the compensation of image motion. The instrument consists of two modules, the adaptive optics assembly and the coronagraph assembly. To the right we show the configuration of the control hardware and the relative interaction of the components. The coronagraph occulting mask M3 is a small $\sim$100 μm diameter Aluminum spot, deposited on a glass window. The mask occults the central star and reimages it into the adaptive optics assembly.

The image motion compensation system consists of a sensor which measures the image offset at 10 ms intervals and converts the offset to a series of three voltages which are input to a high speed tip/tilt mirror. When the fully adaptive system is installed, a wavefront sensor will replace the image motion sensor, while optical flat M1 will be replaced by the adaptive membrane mirror. For operation of the coronagraph with image motion compensation alone a sensor designed around the Tektronix quadrant CCD was used, since this device had been already investigated at Johns Hopkins by W. M. Fastie (1989) as a second generation Fine Guidance Sensor for the Space Telescope.

QUADRANT CCD DESIGN AND CONTROL

The quadrant CCD is a 3-phase frontside illuminated device, manufactured by

Tektronix, and designed specifically for the task of image offset determination. The parallel register consists of four 100 μm^2 pixels, which corresponds to a field of 6 × 6" at the Swope 40 inch telescope at Las Campanas.

Cooling for the quadrant CCD is required to ensure no dark current during an integration. A temperature of -35 to -40^oC is typically necessary to reduce dark noise to negligible levels for the integration times of 10-200 ms required for image motion compensation. We have chosen to cool the devices using thermoelectric (Peltier) stacks which are compact and easy to operate. The quadrant CCD is housed in an evacuated lightweight aluminium dewar and is cooled by means of a 3 or 4 stage thermoelectric cooler. A small fluid bath in the base of the dewar is fed by a closed circuit chiller and maintains the hot face of the thermoelectric cooler at constant temperature. The quadrant CCD package is mounted on a circular circuit board containing the clock and preamplifier circuitry and is coupled to the thermoelectric stack by a short copper finger.

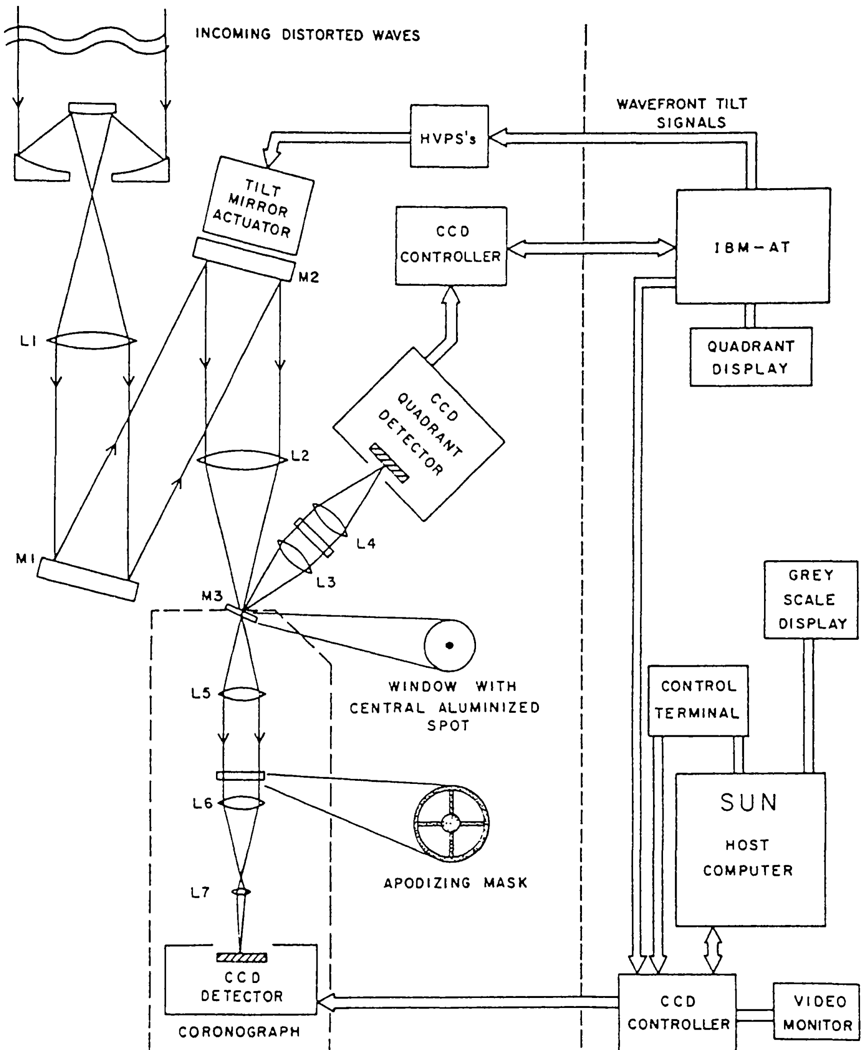

Fig. 1. A Schematic showing the design of the Johns Hopkins adaptive optics coronagraph and its mode of operation when configured for image motion compensation.

The controller electronics for the quadrant CCD are a modified version of the Palomar Observatory system described in detail by Gunn et al. (1987). While the circular board containing clock drivers and preamplifier has been redesigned for the quadrant CCD, the remaining components of the system are essentially unchanged and consist of logic, bias, A/D, signal chain boards and their power supplies. These electronics are packaged in a two small units which mount on the instrument close to the quadrant CCD.

A PC-based data acquisition computer controls the system via a DMA card which interfaces to the CCD controller. In addition to reading the quadrant CCD pixel values, the PC also controls the feedback loop which operates the tip/tilt mirror. Data reads are initiated by sending a linestart signal to the CCD controller. Since it takes 1.2 ms to readout the chip, compute the position error signals and output the corrections to the tip/tilt mirror, CCD integration times of at least 2 ms are needed for operation of the feedback loop. During the computation of position errors, the events are thresholded to discriminate cosmic ray events and if the image position offset exceeds a predefined value the coronagraph's CCD camera shutter is closed. This allows short periods of bad seeing to be rejected in real time, thus improving the quality of the final image. There is a relatively short time lag between measurement of the position offset and application of the tip/tilt mirror correction making the system less susceptible to feedback instabilitics. For a 1 metre telescope typical integration times of 10-20 ms (r_o=10-20 cm) are required to adequately sample the image motion power spectrum.

The system software provides interactive display of the quadrant CCD error signal simplifying the process of aligning and focusing elements within the instrument. During operation of the image motion compensation feedback loop, a real time display provides a plot of the error signal together with data relating to the image motion statistics. Segments of image motion data may also be saved for analysis of atmospheric conditions.

QUADRANT CCD CHARACTERISTICS

The full well of the quadrant CCD is ~500,000 e^- and is adequate for our application. With a system gain of 6.5 $e^- ADU^{-1}$ we have achieved read noise figures as low as ~10 e^-. The quantum efficiency of the device is ~ 50% at 600 nm. The poor blue response below 400 nm is not important for our application since we are primarily interested in imaging in the bandpass 500-900 nm. The uniformity of the device is hard to accurately quantify given its small format, however, with the devices we have used the pixel to pixel non-unformity has ranged from 2%-10 %.

The performance of the quadrant CCD as an image motion sensor is determined by the transfer function in the X and Y directions, given by

$$T_X = (Q_1 + Q_2 - Q_3 - Q_4)/\Sigma Q_N$$

$$T_Y = (Q_1 + Q_4 - Q_2 - Q_3)/\Sigma Q_N$$

respectively, where Q_N is the signal from pixel N in the quadrant CCD. In figure 2 we show two typical transfer curves for the X and Y directions along the chip measured with a 10 μm pinhole image. The two transfer functions show reciprocal gradients of 17 and 13 μm respectively. The slight disparity between the two curves is a result of the electrode architecture of the quadrant CCD masking some areas of the four pixels and a gate electrode (ϕ1) in the center of the parallel register which separates the two rows of pixels in the Y direction. The effect of these electrodes is illustrated by the sum-signal curves which overlay the transfer functions in figure 2. During operation of the image motion compensation system this disparity is corrected by using two different gain factors in calculating the tip/tilt mirror offset.

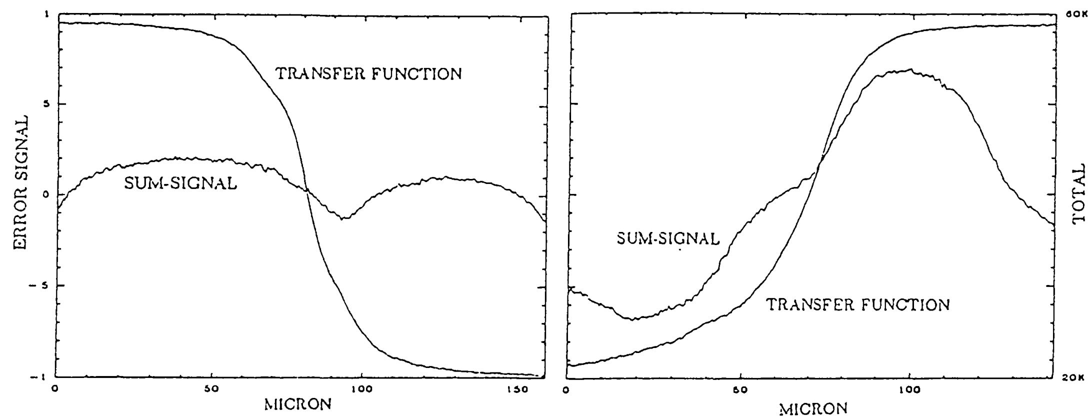

Fig. 2. Plots of the transfer function and sum signal obtained by scanning in the X (right) and Y (left) axes.

An evaluation of the quadrant CCD and it performance in this application may be obtained by considering the noise equivalent angle (NEA), the ratio of total RMS noise for the quadrant at zero displacement divided by the slope of the error signal at zero displacement. In figure 3 we show a plot of the NEA calculated for the Las Campanas 40 inch telescope (f/7) where the coronagraph will be tested. The NEA curve assumes that optical transmission is ~60% and that a broadband filter (100 nm) is placed in front of the quadrant CCD. It may be seen that the system will operate effectively to a limiting magnitude of around 12th magnitude.

RESULTS

In figure 4 we show the results of a simulation to evaluate the performance of the quadrant-CCD operating as an image motion sensor. These experiments were performed with a pinhole image and using a dichroic at position M3 in figure 1, rather than the occulting mask. The left hand image shows the profile of simulated image motion (0.4" contribution), where the power spectrum of the positional offsets applied to the image corresponded to that observed for the atmosphere, giving an image of ~1" FWHM. The right hand image shows the profile obtained with the image motion compensation loop operational, the simulated stellar profile is essentially diffraction limited. The simulation does not take account of the effects of phase distortion in real stellar images, but demonstrates the capability of the system.

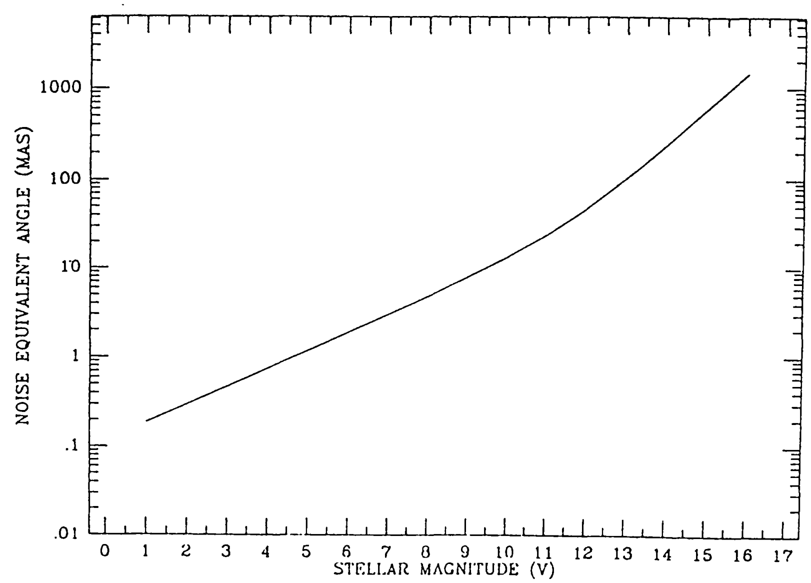

Fig. 3. The noise equivalent angle (NEA) of the quadrant CCD calculated for the operation at the Las Campanas 40 inch.

FURTHER DEVELOPMENTS

A second generation of quadrant CCDs has recently been fabricated which offer improved performance in terms of readout time, read noise and transfer function uniformity. These devices have four separate serial registers, one for each pixel. As a result the readout time is decreased, allowing integration times of the order of μs. Even though the existing quadrant-CCD design is fast enough for our application, the new device will permit us to reduce the time between the CCD read and the output of tip/tilt mirror control voltages still further. In addition, the different electrode structure will eliminate the slight difference in transfer functions resulting from the presence of the channel stop. With on chip preamplifier circuitry, a reduction in readout noise well below 10 e^- can also be expected, increasing the sensitivity of the device.

ACKNOWLEDGEMENTS

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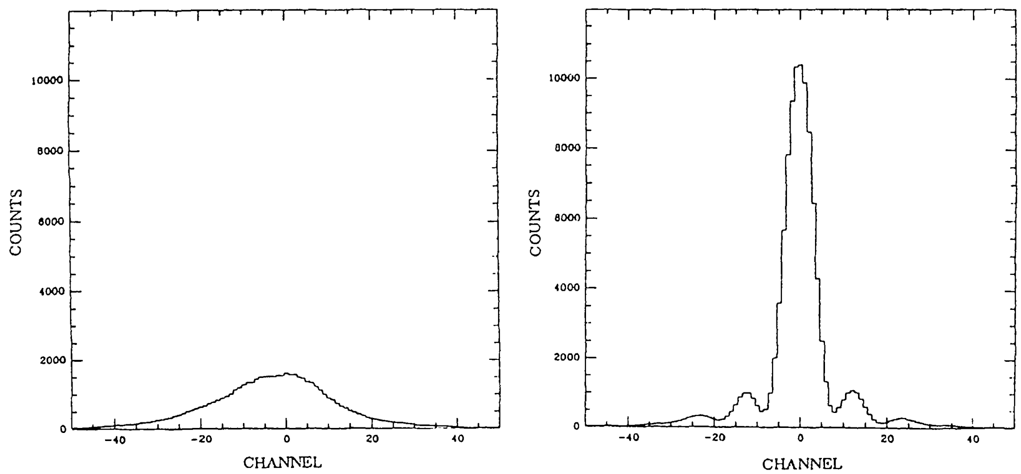

Fig. 4. Profiles of images obtained using image motion simulator showing the uncorrected image on the left and the effect of the image motion compensation on the right.